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# Investigation on the Performance of Low-Profile Insensitive Antenna with Improved Radiation Characteristics for the Future 5G Applications

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***Abstract*****—***A new method to design an insensitive antenna with improved performance for fifth generation (5G) systems is proposed in this letter. In order to improve the antenna performance and also eliminate the effect of high-loss FR-4 substrate, the resonator of the conventional slot antenna has been converted to the air-filled slot-loop structure with a thickness of $h_{sub}$. Since the main substrate of the resonator is the air, the antenna is insensitive for different values of permittivity, loss tangent characteristics of the substrate. So, for different kinds of substrates, the antenna has a same performance in terms of maximum gain, radiation and total efficiencies. The antenna is designed and fabricated on a low-cost* FR4 *substrate and has more than 95% (-0.5 dB) radiation and total efficiencies at 22.25 GHz (center frequency). It has the reflection coefficient ($S_{11}$) less than -10 dB in the frequency range of 21 to 23.5 GHz (more than11% fractional bandwidth) which is one of the candidate bands for future 5G communications. The antenna has a very compact size and could be used in mm-wave phased arrays.*

***Keywords*****—** *5G, insensitive antenna, improved performance, slot-loop antenna.*

## 1. INTRODUCTION

The investigation and development of fifth generation (5G) cellular network have been started recently. Its standardization activity is going to be finalized in 2016 and also the commercial availability of equipment is expected to be approximately in the early of 2020s [1]. One of the key enabling techniques in 5G systems is the use of millimeter-wave antennas at both the mobile device and base station. The millimeter-wave bands could provide bandwidths several times broader than 3G and 4G frequency bands [2-3]. However, moving to this frequency bands would bring new challenges in the designs of antennas [4-8].

One of the challenges in designing antennas at higher frequeicnies is the implementation of antennas using the low-cost materials such as FR4 [5]. The FR4 substrate features good and robust mechanical and electrical characteristics and hence has been widely used in custom electronic products. However, the loss tangent of FR-4 is about 0.025. It is too lossy for millimeter wave antenna designs using traditional antenna structures such as printed patch antenna, where both gain and efficiency of the antenna would be deteriorated [9].

This work deals with designing a novel insensitive slot-loop antenna with improved performance for future 5G applications. The main substrate of the antenna is the air with permittivity of 1 and loss tangent of 0, so it can achieve low loss and high antenna efficiency. The analysis and performance of the antenna are obtained by using CST software [10], and a prototype has been fabricated for experimental verification. The results show that the proposed antenna has good impedance-matching, high efficiencies, acceptable gain level and sufficient radiation patterns characteristics.

## 2. CONFIGURATION OF THE ANTENNA

Configuration of the proposed antenna fed by a discrete port is shown in Fig. 1. The dielectric substance (*FR4*) with thickness of 0.8 mm, relative permittivity of 4.3 and loss tangent of 0.025 is chosen as a substrate to facilitate printed circuit board integration. The antenna has a compact size with overall dimension of $W_{sub} \times L_{sub} \times h_{sub}$.

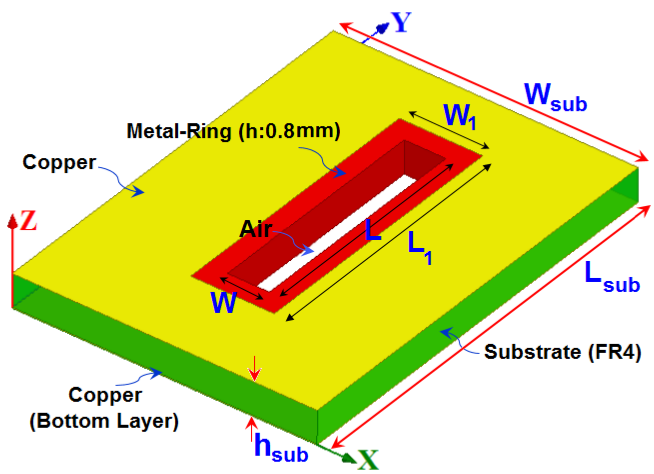



**Fig. 1.** Geometry of the proposed insensitive slot-loop antenna.

This work is started by choosing the dimensions of the conventional slot antenna. The length of the slot is made approximately $\lambda_g/2$and its width is a small fraction of $\lambda_g$. In this study, $\lambda_g$ is the guided wavelength of 22.25 GHz (center frequency). As the effect of substrate (FR4) has been removed, for the proposed design the length of the resonator must be calculated near $\lambda/2$. Hence, the essential parameters for the design are: $f_0$=22.25 GHz (resonance frequency), $\varepsilon_r$=4.3 and $h_{sub}$=0.8 mm.

The dimension values of proposed design parameters are as follow: $W_{sub}$=5 mm, $L_{sub}$=10 mm, W=0.5 mm, L= 7.25 mm, $W_1$= 1.5 mm, and $L_1$=8.25 mm.

## 3. RESULTS

### *A. Slot Antenna*

Configuration of the conventional slot antenna consists of a radiator formed by cutting a narrow slot in a large metal (copper) surface. The length of slot is a half guided wavelength and its width is a small fraction of a wavelength. The antenna radiates in a way similar to a conventional half-wave dipole antenna two flat metal arms. In general, this type of antenna is called the complementary dipole [11]. Configuration of the conventional slot antenna is shown in Fig. 2.

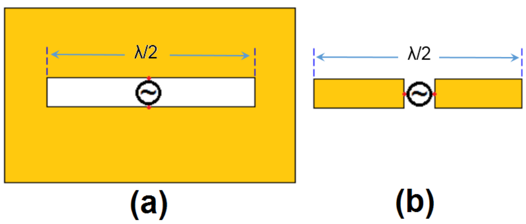



**Fig. 2.** (a) Conventional slot antenna, and (b) its complementary structure.

In this study, we started by designing simple slot antenna for 22.25GHz. Configuration of designed slot antenna is shown in Fig. 3 (a). The antenna is designed on an FR4 substrate. In order to have a high efficiency antenna, a cubic hole with length of the λ/2 has been applied inside antenna substrate. In addition, by adding a metal-ring resonator inside the hole, the insensitivity characteristic of the antenna can be obtained.

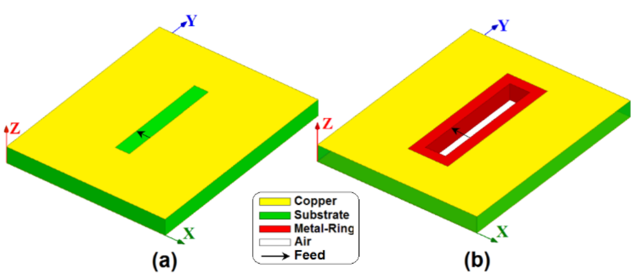



**Fig. 3.** Configuration of the 22.25 GHz antennas, (a) conventional slot antenna, (b) proposed metal-ring slot-loop antenna.

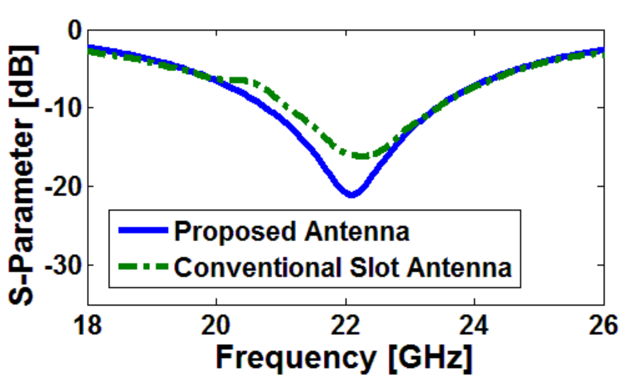
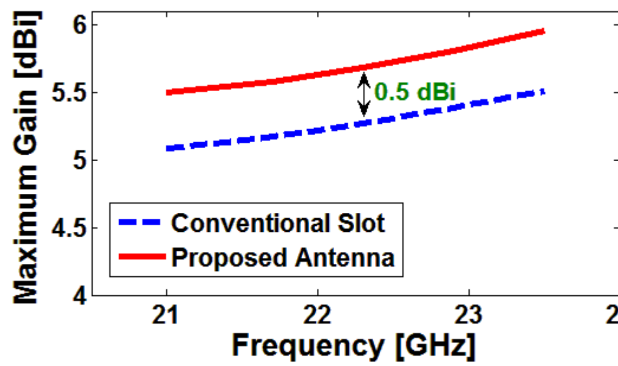



**Fig. 4.** Simulated reflection coefficient characteristics of the antennas shown in Fig. 3.

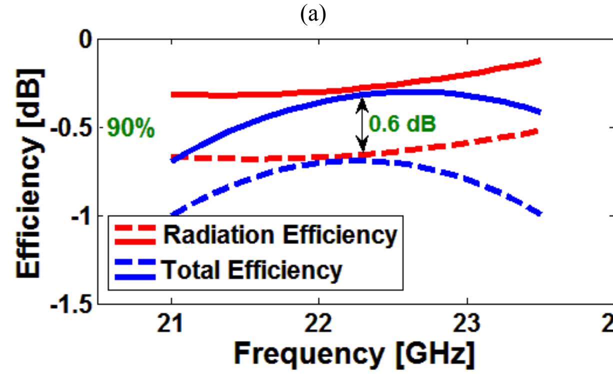
Figure 4 shows the simulated reflection coefficient ($S_{11}$) characteristics of the antennas shown in Fig. 3. Simulated results obtained for these antennas show that both of them have good behaviors at the frequency range of 21 to 23.5 GHz. The configuration of the conventional slot antenna and the proposed antenna designed to operate at 22.25 GHz are shown in Fig. 3. As shown, the discrete-port feeding has been used to feed the simulated antennas.

### *B. Improved Performance of the Antenna*

In the proposed design, by cutting the substrate of conventional slot antenna, maximum gain and efficiency characteristics of the antenna are improved. In addition, in order to achieve the insensitivity characteristic, an air-filled metal-ring with thickness of $h_{sub}$ has been used inside the cut slot.




(a)




(b)

**Fig. 5.** Comparison between (a) maximum gain, and (b) antenna efficiencies of the conventional slot (dash-line) and proposed metal-ring slot-loop (solid-line) antennas.

Figure 5 depicts the comparison between maximum gain, radiation and total efficiencies of the conventional slot and the proposed antenna. As illustrated in Fig. 5 (a), by using the proposed design (slot-loop antenna), the maximum gain characteristic of the antenna can be improved about 0.5 dBi. Additionally, it can be seen in Fig. 5 (b) the radiation and total efficiencies of the antenna are improved about 0.6 dB in the frequency band from 21 GHz to 23.5 GHz.

*C. Insensitivity Characteristic of the Proposed Antenna*

In this section, the results of investigation on insensitivity property of the design have been studied.

In general, permittivity ($\varepsilon_r$) and loss tangent ($\delta$) of the dielectric substrate are critical parameters in controlling frequency bandwidth, and efficiency characteristics of the antenna [12-13]. The main novelty of this study is the insensitivity characteristic of the antenna for different values of permittivity and loss tangent which has been investigated in Figs. 6, 7, and 8.

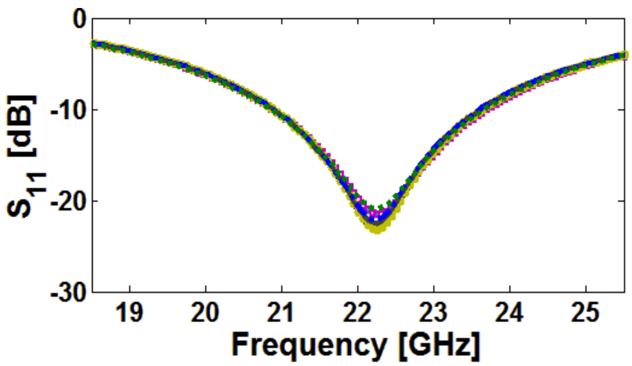



**Fig. 6.** Simulated $S_{11}$ characteristics of the antenna for different values of permittivity ($\varepsilon_r$: from 2 to 5.5).

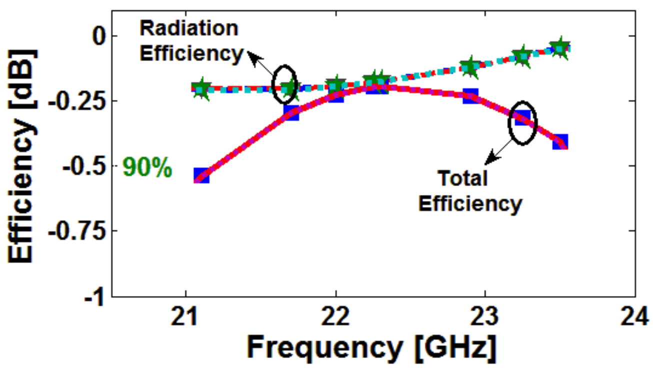



**Fig. 7.** Simulated antenna efficiencies for different values of loss tangent ($\delta$: form 0.005 to 0.055).

As illustrated, when the values of the antenna permittivity and loss tangent increase respectively from 2 to 5.5 and from 0.005 to 0.055, the antenna has same performance in terms of $S_{11}$, efficiencies (radiation and total), and maximum gain. From this result, we can conclude that the different types of substrate with different values of $\varepsilon_r$ and $\delta$ could be used for the proposed insensitive antenna. Furthermore, it can be found at the center frequency of operation band (22.25 GHz), the proposed antenna has same values of efficiency for radiation and total efficiency characteristics (more than 95%). From these results, we can conclude that the proposed design is insensitive for different values of $\varepsilon_r$ and $\delta$ and could have same performances for different kinds of antenna substrates.

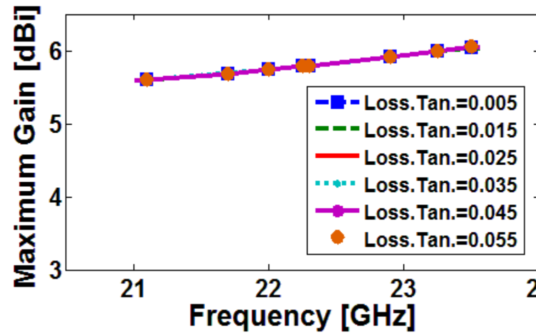



**Fig. 8.** Simulated maximum gain characteristics of the proposed antenna for different values of loss tangent.

In order to known the phenomenon behind the insensitive characteristic of proposed design, the simulated current distributions for 22.25 GHz for both of the structures are presented in Fig. 9. It can be observed in Fig. 9 (a), compared with slot antenna with cut-substrate, the current flows are just dominant around of the metal-ring structure. Which means the metal-ring structure with thickness of $h_{sub}$ is the main resonator of the proposed design and its behavior is not effected with the substrate properties [14].

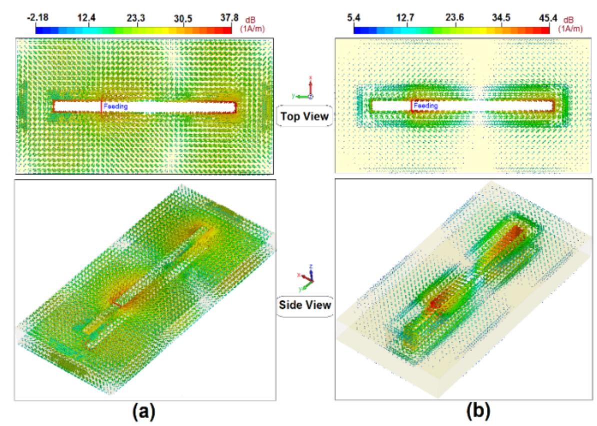



**Fig. 9.** Current distributions at 22.25 GHz for (a) slot antenna with cut substrate, (b) proposed metal-ring slot antenna.

The proposed antenna with final design has been fabricated in a standard FR-4 PCB substrat. During the fabrication, a rectangular-cavity slot for holding the elements was made on the FR-4 substrate. The metal-ring element was made seperately using a milling machine and inserted into the slot. The photograph of the fabricated antenna is shown in Fig. 10.

For measuring the antenna reflection cofiicient ($S_{11}$) characteristic, a coaxial cable was used for feeding the antenna resonator (the inner conductor was extended from one side to the another side of the air-filled metal-ring resonator). Simulated and measured $S_{11}$ of the antenna is also shown in Fig. 10. As seen, the antenna has a good frequency response over the frequency range of 21 to 23.5 GHz which is one of the candidate bands for 5G communication systems [15].

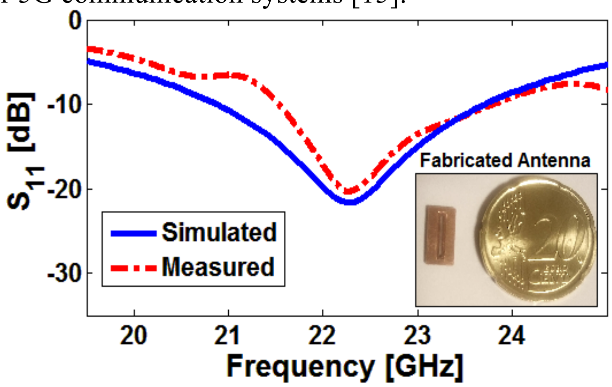



**Fig. 10.** Measured and simulated reflection coefficient ($S_{11}$) of the fabricated antenna.

3D radiation patterns of the antenna at different frequencies over the operation frequency range are presented in Fig. 11. As seen, the proposed antenna has good radiation behavior with acceptable realized gain levels entire the operation band.

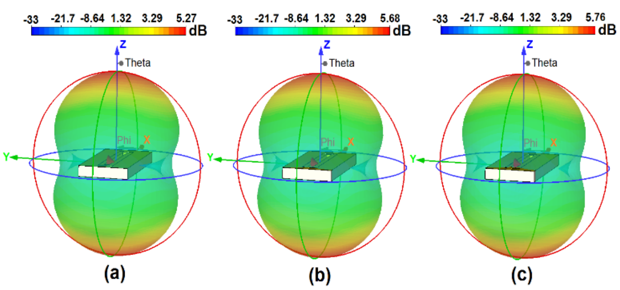



**Fig. 11.** 3D radiation patterns of the proposed antenna with realized gain values at, (a) 21 GHz, (b) 22.25 GHz, and (c) 23.5 GHz.

As mentioned above, the proposed design could be used in the future 5G cellular devices. Figure 12 illustrates the configuration and also 3D radiation beams of a phased array mobile-phone antenna designed using the proposed radiators. It contains eight elements of the proposed antenna elements placed on the top portion of the mobile-phone PCB. Another set of the phased array could be used at bottom portion of the PCB. As can be observed the designed mobile-phone antenna has good radiation characteristics in terms of beam-steering, efficiency and gain values at 22.25 GHz (resonance frequency).

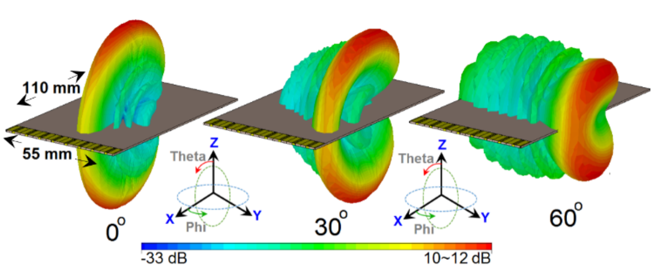



**Fig. 12.** 3D radiation beams of the mobile-phone phased array antenna.

## 4. CONCLUSION

In this study, a new and low-profile design of insensitive air-filled slot-loop antenna for 5G communications is presented. The proposed antenna is designed on a low-cost substrate (FR4) to operate at 21-23.5 GHz. The proposed antenna has good performance in terms of reflection coefficient, efficiency, and radiation pattern characteristics. The results are presented to validate the usefulness of the antenna for 5G applications.

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